REPORT DOCUMENTATION PAGE

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Final Report: A Large Outdoor Motion-tracking Arena for Research on Heterogeneous Autonomous Multi-robot Systems

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UU	UU	UU	UU		19b. TELEPHONE NUMBER: 951-827-6132

RPPR Final Report
as of 02-Aug-2021

Agency Code: 21XD

Proposal Number: 72117CSRIP **Agreement Number: W911NF-18-1-0266**

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Report Date: 24-Oct-2020 Date Received: 20-Jul-2021
Final Report for Period Beginning 29-Jul-2018 and Ending 24-Jul-2020
Title: A Large Outdoor Motion-tracking Arena for Research on Heterogeneous Autonomous Multi-robot Systems
Begin Performance Period: 29-Jul-2018 **End Performance Period:** 24-Jul-2020
Report Term: 0-Other
Submitted By: Amit Roy-Chowdhury Email: amitrc@ece.ucr.edu
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:**

Major Goals: This DURIP project aims to establish robotics experimentation and testing facilities instrumented with high-speed motion tracking cameras at UCR. Two facilities have been enabled through support of this DURIP. 1) An indoor 23ft L. x 29ft W. x 10ft H. 12-camera space (completed and fully operational), and 2) an outdoor 80ft L. x 40ft W. x 25ft H. 40-camera space (final stages of completion are under way because of COVID-19 challenges). The proposed research infrastructure is indispensable to the research and relevant research-related education activities associated with current and pending Department of Defense (DoD) projects at UCR. At its core, the requested infrastructure offers millimeter-accurate position and orientation (pose) measurements both indoors and outdoors. Availability of trustworthy, high-accuracy pose information outdoors is critical for testing and validating the performance of multi-robot planning, navigation and control algorithms in realistic settings. Having accurate localization systems for both indoor and outdoor operation also permits research involving transition in variable lighting settings, which can affect on-board state estimation (e.g., via RGB cameras and LiDARs).
Faculty in the Departments of Electrical and Computer Engineering and Mechanical Engineering have access to the instrumentation for research purposes. The outdoor facility will be especially useful for courses in robotics,

autonomy, machine intelligence, and control of multi-agent systems comprising heterogeneous (ground and aerial) vehicles, which span the expertise of the PIs involved in this effort. DURIP funds were cost-shared with UCR funds that cover the construction costs of an outdoor metal truss to house the motion capture system.

Accomplishments: The original plan was to implement a single outdoor motion capture facility. The UCR cost-shared funds, however, also allowed to also add a smaller indoor motion capture facility. The latter was completed fast, and has been fully operational; two conference papers have appeared and more results are forthcoming. The outdoor facility is at the time of writing, still under development. The motion capture camera system has been procured; however, construction of the truss to house the cameras is still under way because of several long-lasting COVID-19 delays. In more detail, the metal truss has been procured and delivered. Professional engineering design of the truss facility and all required permits have been obtained. Construction of concrete footings to support the truss is currently underway.

Training Opportunities: Two PhD students and one MS students have utilized the indoor motion capture system extensively, leading to four top-tier robotics conference publications. The research in these papers is in support of a current ONR project (as well as other NSF projects) that PI Karydis is part of.

PhD students: Zhouyu Lu, Zhichao Liu
MS student: Gustavo Correa

Results Dissemination: Four papers in top robotics conferences (ICRA, IROS) have been produced so far.

Honors and Awards: Karydis:
- Regents Faculty Fellowship (2019)

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Konstantinos Karydis
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: Amit Roy-Chowdhury
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: Fabio Pasqualetti
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: Jay Farrell
Person Months Worked: 1.00 **Funding Support:**

Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: Anastasios Mourikis
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Zhichao Liu
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Zhouyu Lu
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Gustavo Correa
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

CONFERENCE PAPERS:

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Conference Name: IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)
Date Received: 20-Jul-2021 Conference Date: 27-Sep-2021 Date Published: 27-Sep-2021
Conference Location: Prague, Czech Republic
Paper Title: Deformation Recovery Control and Post-impact Trajectory Replanning for Collision-resilient Mobile Robots
Authors: Zhouyu Lu, Zhichao Liu, Konstantinos Karydis
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 02-Aug-2021

Publication Type: Conference Paper or Presentation **Publication Status:** 3-Accepted
Conference Name: IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)
Date Received: 20-Jul-2021 Conference Date: 27-Sep-2021 Date Published: 27-Sep-2021
Conference Location: Prague, Czech Republic
Paper Title: Position Control and Variable-Height Trajectory Tracking of a Soft Pneumatic Legged Robot
Authors: Zhichao Liu, Konstantinos Karydis
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2020 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)
Date Received: 20-Jul-2021 Conference Date: 24-Oct-2020 Date Published:
Conference Location: Las Vegas, NV, USA
Paper Title: Motion Planning for Collision-resilient Mobile Robots in Obstacle-cluttered Unknown Environments with Risk Reward Trade-offs
Authors: Zhouyu Lu, Zhichao Liu, Gustavo Correa, Konstantinos Karydis
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 2-Awaiting Publicat
Conference Name: 2021 IEEE Int. Conf. on Robotics and Automation (ICRA)
Date Received: 20-Jul-2021 Conference Date: 30-May-2021 Date Published: 30-May-2021
Conference Location: Xi'an, China
Paper Title: Toward Impact-resilient Quadrotor Design, Collision Characterization and Recovery Control to Sustain Flight after Collisions
Authors: Zhichao Liu, Konstantinos Karydis
Acknowledged Federal Support: **Y**

Partners

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I certify that the information in the report is complete and accurate:
Signature: Konstantinos Karydis
Signature Date: 7/20/21 1:33PM

ARL-W911NF-18-1-0266, DURIP: A Large Outdoor Motion-tracking Arena for Research on Heterogeneous Autonomous Multi-robot Systems

FINAL REPORT

Reporting Period: 7/29/2018 - 7/24/2020

Submitter: Konstantinos Karydis

Location of Project: University of California, Riverside (UCR)

Project Personnel: Konstantinos Karydis (PI)

Jay Farrell (Co-PI)

Anastasios Mourikis (Co-PI)

Fabio Pasqualetti (Co-PI)

Amit Roy-Chowdhury (Co-PI)

Distribution Statement: Approved for public release; distribution is unlimited.

Project Objective

This DURIP project aims to establish robotics experimentation and testing facilities instrumented with high-speed motion tracking cameras at UCR. Two facilities have been enabled through support of this DURIP. 1) An indoor 23ft L. x 29ft W. x 10ft H. 12-camera space (completed and fully operational), and 2) an outdoor 80ft L. x 40ft W. x 25ft H. 40-camera space (final stages of completion are under way because of COVID-19 challenges).

The proposed research infrastructure is indispensable to the research and relevant research-related education activities associated with current and pending Department of Defense (DoD) projects at UCR. At its core, the requested infrastructure offers millimeter-accurate position and orientation (pose) measurements both indoors and outdoors. Availability of trustworthy, high-accuracy pose information outdoors is critical for testing and validating the performance of multi-robot planning, navigation and control algorithms in realistic settings. Having accurate localization systems for both indoor and outdoor operation also permits research involving transition in variable lighting settings, which can affect on-board state estimation (e.g., via RGB cameras and LiDARs).

Faculty in the Departments of Electrical and Computer Engineering and Mechanical Engineering have access to the instrumentation for research purposes. The outdoor facility will be especially useful for courses in robotics, autonomy, machine intelligence, and control of multi-agent systems comprising heterogeneous (ground and aerial) vehicles, which span the expertise of the PIs involved in this effort. DURIP funds were cost-shared with UCR funds that cover the construction costs of an outdoor metal truss to house the motion capture system.

Accomplishments

The original plan was to implement a single outdoor motion capture facility. The UCR cost-shared funds, however, also allowed to also add a smaller indoor motion capture facility. The latter was completed fast, and has been fully operational; two conference papers have appeared and more results are forthcoming. The outdoor facility is at the time of writing, still under development. The motion capture camera system has been procured; however, construction of the truss to house the cameras is still under way because of several long-lasting COVID-19 delays. In more detail, the metal truss has been procured and delivered. Professional engineering design of the truss facility and all required permits have been obtained. Construction of concrete footings to support the truss is currently underway.

Ongoing Work to Mitigate Impact of COVID-19

COVID-19 had a major impact on our capability to complete the outdoor motion capture facility before the end of the project's period and continuing uncertainties in an expected completion date were in place even after the formal end of the project's period. Currently, we are on track to

complete the facility in Summer 2021. We expect to have the outdoor system fully operational by Fall 2021, as we enter into more in-person campus activities. At the same time, we have already procured various ground and aerial robots so that we are ready to use the facility as soon as it is fully completed. We expect a series of new and exciting results to be forthcoming once the outdoor motion capture facility is operational.

Training Opportunities

Two PhD students and one MS students have utilized the indoor motion capture system extensively, leading to four top-tier robotics conference publications. The research in these papers is in support of a current ONR project (as well as other NSF projects) that PI Karydis is part of.

PhD students: Zhouyu Lu, Zhichao Liu

MS student: Gustavo Correa

Results Dissemination

[1] Z. Lu, Z. Liu, and K. Karydis, Deformation Recovery Control and Post-impact Trajectory Replanning for Collision-resilient Mobile Robots. In IEEE\RSJ Int. Conf. on Intelligent Robots and Systems (IROS), 2021. In Print.

[2] Z. Liu and K. Karydis, Position Control and Variable-Height Trajectory Tracking of a Soft Pneumatic Legged Robot. In IEEE\RSJ Int. Conf. on Intelligent Robots and Systems (IROS), 2021. In Print.

[3] Z. Liu and K. Karydis, Toward Impact-resilient Quadrotor Design, Collision Characterization and Recovery Control to Sustain Flight after Collisions. In IEEE Int. Conf. on Robotics and Automation (ICRA), 2021. In Print.

[4] Z. Lu, Z. Liu, G. Correa, and K. Karydis, Motion Planning for Collision-resilient Mobile Robots in Obstacle cluttered Unknown Environments with Risk Reward trade-offs. In IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS), 2020, pp. 7064-7070.

Appendix

Electronic copies of the four papers referenced above are enclosed.